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Survey of Passive Leak Detection Technologies for Membrane Roofing

by
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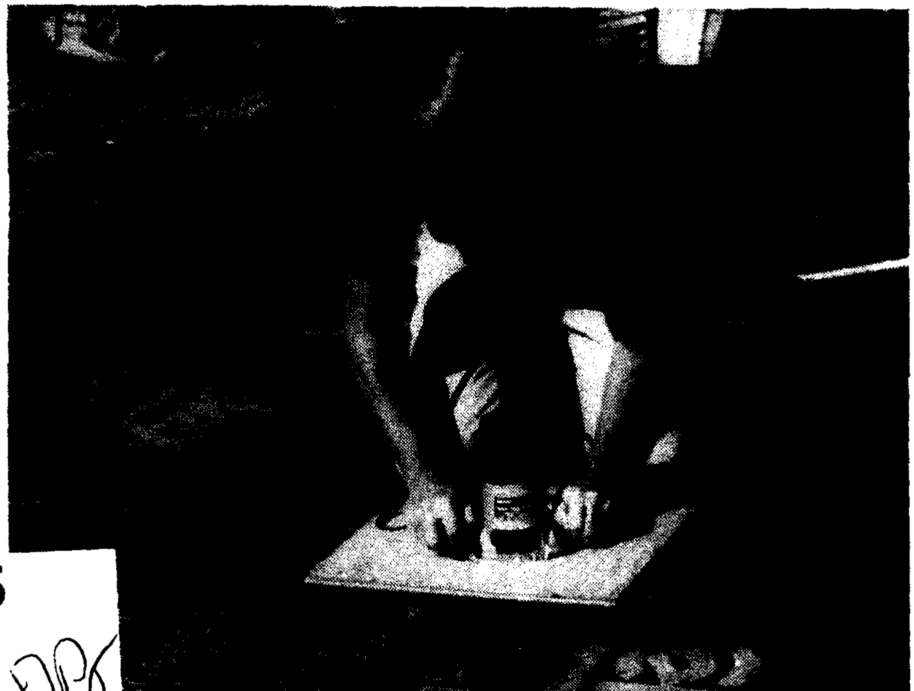

The U.S. Army has a large inventory of buildings with low-slope membrane roofs. Eventually, most of these roofs will experience flaws that allow water intrusion. The cost resulting from water damage to the roofing system, structure, and building contents that can occur between the time a leak begins and is located and repaired can be very high. A passive roof leak detection system (PRLDS) could help Army managers by providing early leak detection and could potentially reduce the Army's roofing maintenance budget.

This study determined that a PRLDS contains four components: sensors, signal, transmission medium, and signal processing unit. The sensors can be resistive, capacitive, circuit-bridging, or fiber optics.

Sensor placement and spacing on a roof determine the system's "resolution" and should be based on the system cost and the interior use of the structure. A discussion of the reliability, compatibility, durability, and maintainability of components is included.

This study also determined that several moisture-sensing technologies are feasible, including a water-activated battery/transmitter, a variety of probes, moisture detection tape, and coated wires. Because little documented experience with these new technologies exists, it is recommended that field investigations be conducted and design specifications be developed.

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13. ABSTRACT (Maximum 200 words)

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Foreword

This study was conducted for Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162784AT41, "Military Facilities Engineering Technology"; Work Unit C53, "Smart Roofing Systems." The technical monitor was Rodger Seeman, CEMP-EA.

The work was performed by the Engineering and Materials Division (FM) of the Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). David Bailey is the principal investigator. Rene Dupuis is a principal researcher and Andrew Buckner is a research technician with Structural Research, Inc. of Madison, WI. Dr. Paul Howdyshell is Chief, CECER-FM, and Dr. Michael J. O'Connor is Chief, CECER-FL. The USACERL technical editor was Gloria J. Wienke, Information Management Office.

LTC David J. Rehbein is Commander, USACERL, and Dr. L.R. Shaffer is Director.

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1 Introduction

Background

The U.S. Army has a large inventory of buildings with low-slope membrane roofs, including built-up, single-ply, and sprayed polyurethane foam roofing. Depending on location and use, most of these roofs contain insulation of varying type and thickness. During their service lives, the vast majority of these roofs experience at least some flaws in the roof covering, which allow water intrusion. Especially with insulated roofs, large quantities of water can enter the roofing system before it actually shows up in the building interior. Once a leak is identified, it can be very difficult to locate the source of the leak on the rooftop.

The cost resulting from water damage to the roofing system, structure, and building contents that can happen between the time a leak occurs and is located and repaired can be very high. Considering the vast array of roof sizes and types, and the critical need for maintaining watertight integrity on housing, training, and operations facilities, a passive roof leak detection system (PRLDS) could help Army maintenance managers by providing early leak detection and could reduce the Army's maintenance budget for roofs.

Objective

The objective of this research is to determine the requirements for a PRLDS and to identify, describe, and provide a preliminary assessment of moisture-sensing and PRLDS technologies for use with membrane roofing.

Approach

Researchers conducted an extensive literature survey of moisture-sensing technologies and roof leak detection systems. Based on information from the literature review, the following steps were performed to accomplish the objective of the study:

1. Describe a PRLDS including system function, components, and configuration,
2. Determine the performance requirements for a PRLDS, and
3. Identify and describe (a) PRLDSs that are currently being developed or are available for use and (b) moisture-sensing technologies that exhibit potential for practical application with PRLDSs.

Mode of Technology Transfer

This research provides the initial phase in the development of design specifications for a passive roof leak detection capability for the Army. Results of this and subsequent studies will be published in relevant research journals and presented at roofing research symposia. It is recommended that the final outcome of this research be the development of a Corps of Engineers Guide Specification for PRLDS for membrane roofs.

2 Description of a Passive Roof Leak Detection System

System Function

Moisture sensors placed in a roofing system can provide early detection of moisture intrusion from roof leaks. This capability can allow maintenance personnel to take prompt responsive action to correct the problem, which can greatly reduce damage to the roofing system, building interior, and contents. A leak detection system also has a secondary benefit of improving the ability to locate flaws that cause the leaks in the roofing system. Locating the source of a leak can be a difficult task in many cases, especially for loose-laid and mechanically fastened roofing systems that may allow water to migrate great distances laterally before entering the building interior. It is also difficult to locate leaks in ballasted membrane systems, which are covered with stones or pavers.

A passive roof leak detection system uses sensors placed in the roof to detect water intrusion from flaws in the roofing system. The sensors either lie dormant until moisture activates them or they provide a continuous capability to monitor the moisture content within the roof. A PRLDS differs from the use of nondestructive methods such as infrared thermography, nuclear meters, and capacitance meters to detect wet insulation and find roof leaks. These methods require frequent, regular surveys to provide early leak detection.

System Components

The four major components of a PRLDS are: sensors, a signal, transmission medium, and a signal processing unit. The sensors are devices that respond to a stimulus of liquid water or high levels of moisture in the form of vapor, and generate and transmit a resulting impulse or signal. The signal is passed through a transmission medium to a signal processing unit where it can be deciphered and processed.

Sensor

In this study, the sensors that can be used to monitor leak water in roofing systems have been grouped into four types: resistive, capacitive, circuit-bridging, and fiber optic sensors. The first two types are impedance-based sensors that measure changes in electrical properties. Circuit-bridging sensors use moisture to provide an electrical connection for an alarm. Fiber optic sensors rely on external forces impinging on the optical fiber or, alternatively, they may detect changes in transmission characteristics due to the presence of moisture.

Resistive Sensors. Resistive sensors have been used to study the moisture content of wood (Duff 1966) and soil (Schmugge, Jackson, and McKim 1980; Posada, Liou, and Miller 1991; Topp, Davis, and Annan 1980). Sensors of this type measure the moisture content of a material by monitoring its electrical resistance. Since water contained in wood or soil is a good conductor, the electrical resistance will decrease as the material becomes wet. The electrical resistance of a material can be determined by passing a known current directly through the material and measuring the voltage difference between two electrodes, or by measuring the electrical resistance of another material that is in hydrostatic equilibrium with the material of interest (Schmugge, Jackson, and McKim 1980).

A basic circuit diagram for a resistive sensor is shown in Figure 1. A constant current is introduced into the circuit and passes through the material under test. The voltage across the electrodes is monitored and related to the electrical resistance of the material through,

$$R = V/I \qquad \text{[Eq 1]}$$

where I is the current flowing in the circuit and V is the voltage across the electrodes. A calibration curve must be used to relate the resistance to the moisture content of the material. An example of a calibration curve for a resistive sensor is shown in Figure 2. Using such a curve, resistive sensors can be used to detect a range of moisture contents.

Capacitive Sensors. Capacitive sensors measure the change in the dielectric constant of a material. The dielectric constant gives a measure of the ability of a material to store electrical energy. A mixture of materials has an apparent dielectric constant that is equal to the sum of the product of the dielectric constant of each constituent and its concentration in the mixture. The dielectric constant of water is around 80 while the dielectric constant of most types of insulation (when dry) is between 1 and 4 (Bushing, Mathey, and Rossiter Jr. 1978). When insulation absorbs moisture and becomes wet, the

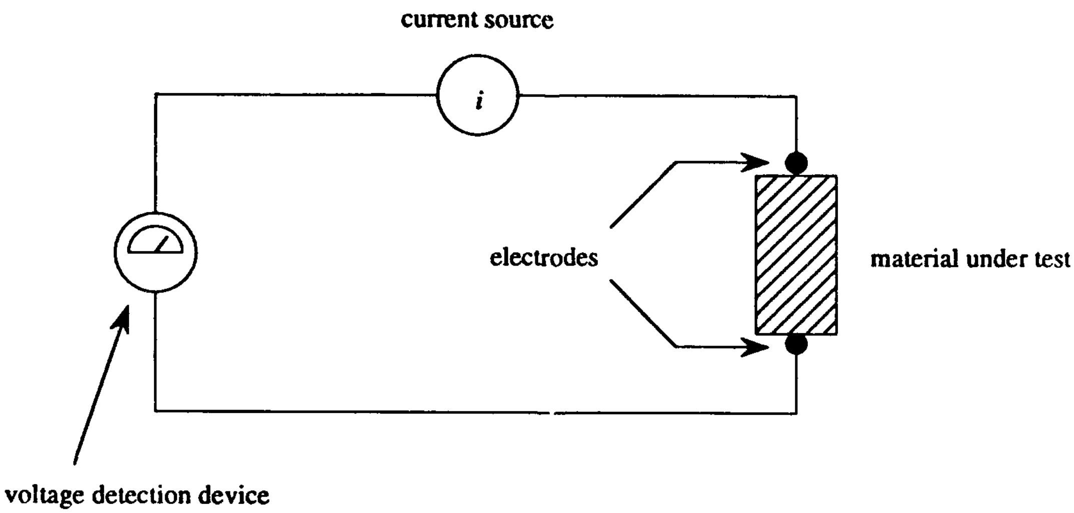
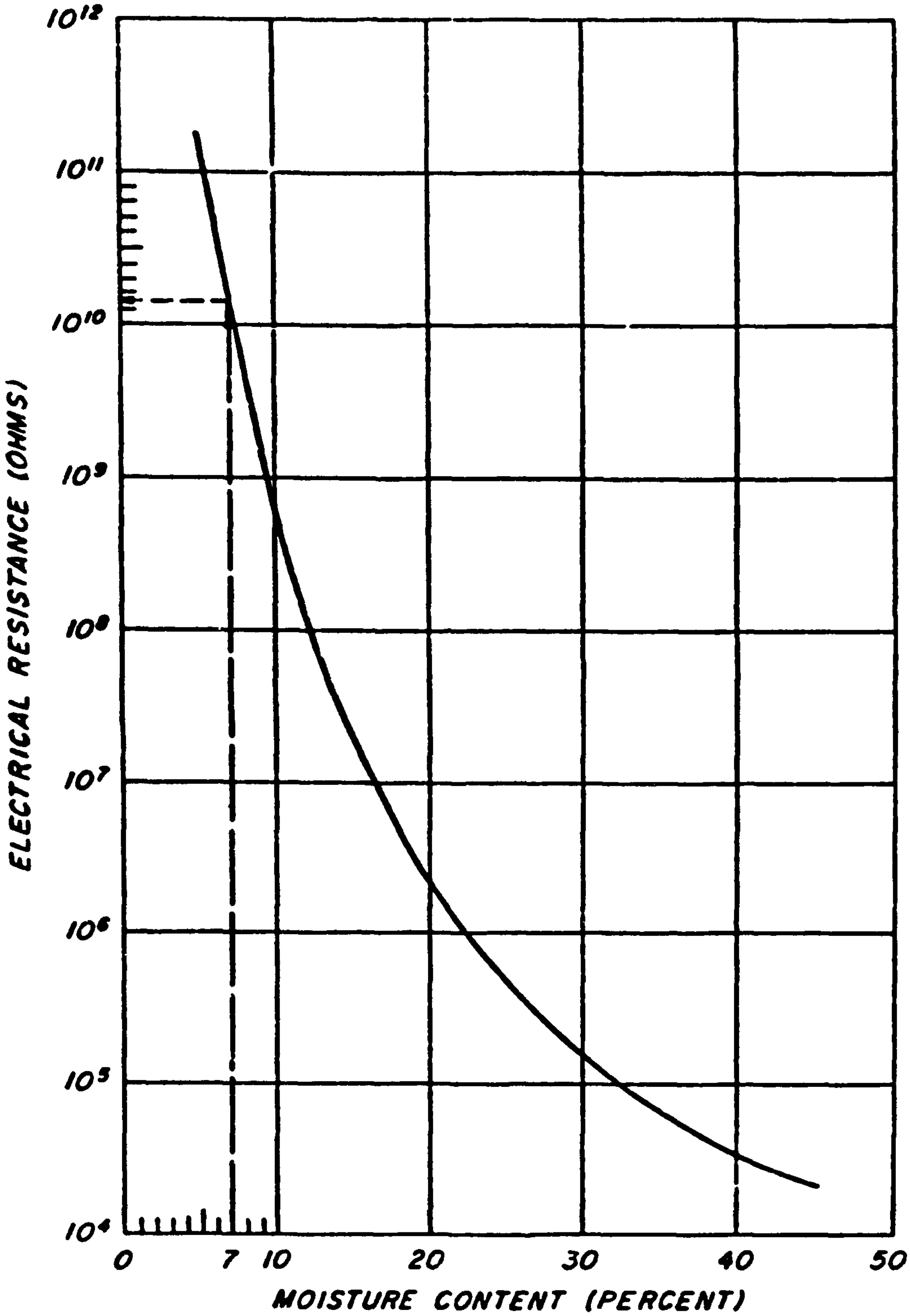


Figure 1. Basic circuit diagram for a resistive sensor.



(Duff 1966)

Figure 2. Calibration curve for a resistive sensor.

dielectric constant increases. Changes in the dielectric constant of a material normally are measured by monitoring departures from a reference capacitance. Like the resistive sensors, capacitive sensors require the use of a calibration curve.

Three methods that use capacitance measurements to detect moisture have been identified. In the first method, the capacitance can be measured directly by using the insulation material as the dielectric medium between two parallel plates, which serve as the electrodes (Stafford 1988). Through the use of a pair of wires, the leads from the sensor are connected to an impedance bridge (Posada, Liou, and Miller 1991) from which the capacitance of the material can be read directly (Figure 3).

The second method uses the same sensor configuration as the first method, but monitors the change in capacitance in a different way. With this sensor, the capacitance of the material under test is used in an L-C resonant (inductor-capacitor) circuit of an oscillator. A change in the capacitance of the material due to moisture (Wobschall 1978) will cause a frequency shift of the resonant peak of the oscillator (Figure 4).

The third method is based on time domain reflectometry (TDR). A pulse, radio frequency electromagnetic wave is passed through a transmission line and its propagation velocity is determined by detecting the reflected pulse from the end of the line, measuring the time delay between transmitted and reflected pulses, and determining the distance traveled. The velocity depends on the dielectric constant (capacitance) of the material (Topp, Davis, and Annan 1980). The propagation velocity is faster when the material is wet than when it is dry.

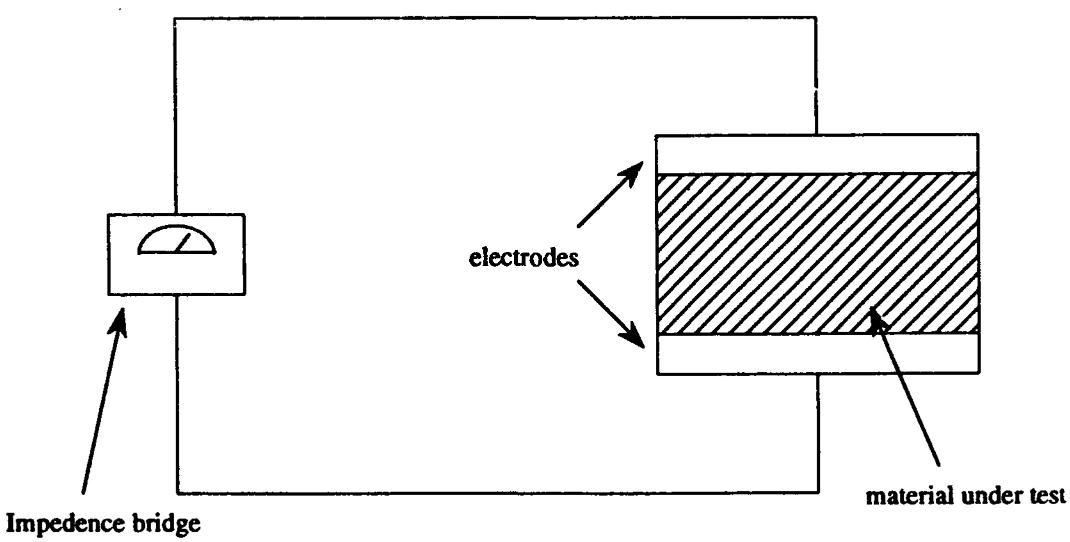


Figure 3. Capacitance sensor with dielectric medium between parallel plates.

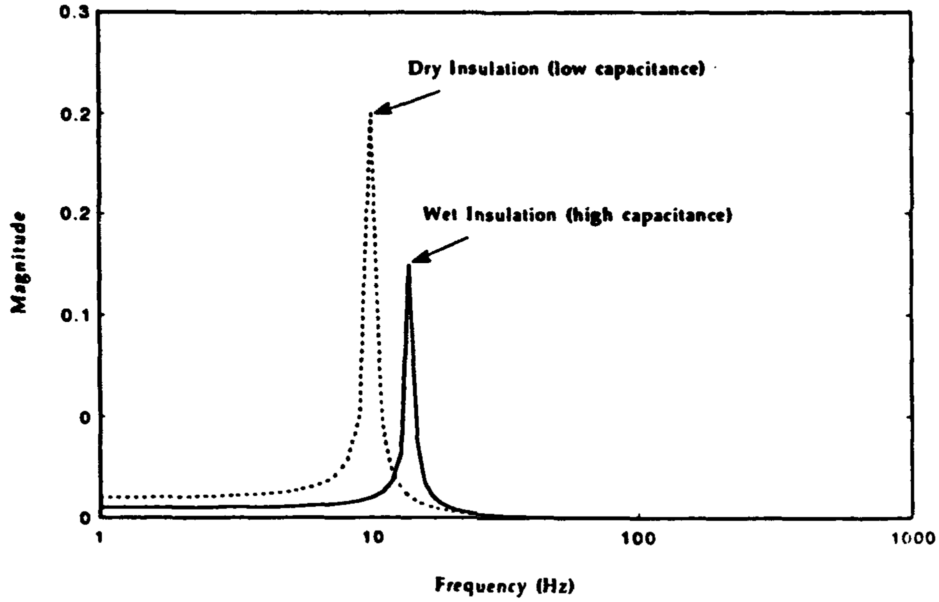


Figure 4. Frequency shift of an L-C resonant circuit due to change in capacitance.

Circuit-bridging Sensors. Circuit-bridging sensors use moisture to bridge an insulating gap and provide an electrical connection between two electrodes. This type of sensor has been used to monitor moisture intrusion at fiber optic splice locations and in suspended ceilings and subfloorings of rooms that contain sensitive equipment (Dorelan Products 1992; Ross and Sontag 1987). Circuit-bridging sensors may not rely on a property of the material under test, but instead require a set amount of moisture to activate the circuit. Once the circuit is activated, the moisture's presence can be indicated by a transmitted signal.

One configuration of a circuit-bridging sensor uses electrodes embedded in a moisture-absorbing cloth that carries a salt. When the cloth becomes wet, the salt dissolves and the ions provide conductivity between the two electrodes (Knoll and Woods 1980). When enough moisture is absorbed to form a solution, the circuit will be closed and current will flow. Another circuit-bridging sensor has two wire electrodes embedded in a nonhygroscopic tape. This moisture detection tape is described in Chapter 4.

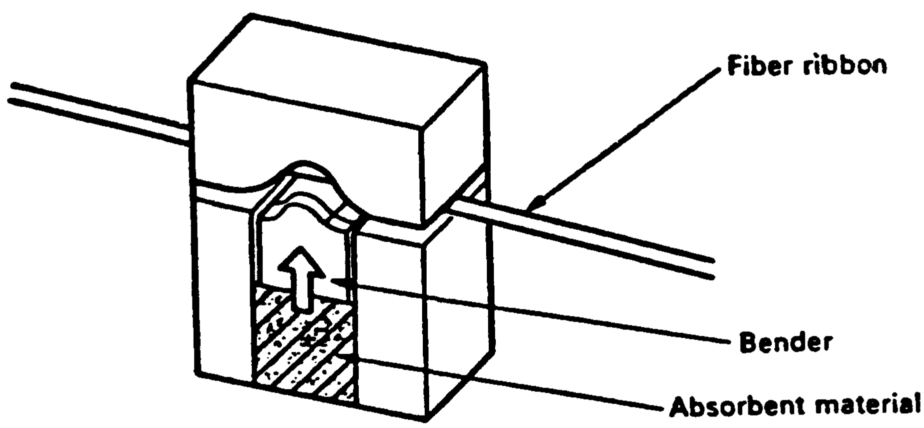
Two different circuit-bridging sensors have been proposed for monitoring moisture ingression in low slope roofs (discussed in Chapter 4). The first, which is currently being marketed, is a sensor unit consisting of a water-activated battery with a miniaturized radio transmitter (Bryan 1986; MID Systems 1992). When enough water is collected at the sensor to bridge the circuit, the transmitter sends a digitally encoded radio frequency signal through the air to a remote receiver.

The second sensor is a resistance probe in the developmental stage (Industrial Options 1992). With this sensor, deviations from a nominal voltage are used as an indication of moisture. The sensor uses a variable resistor in parallel with a set of probes. A constant current is passed through the circuit and a nominal voltage level is established for the system with dry insulation. When the insulation becomes wet, its resistance drops, thus reducing the effective resistance in the circuit. The sensor does not quantify the amount of moisture with a calibration curve and is therefore considered a circuit-bridging sensor.

Fiber Optic Sensors. Fiber optic sensors have become popular within the past 10 years for use as embedded sensors in composite structures for purposes other than moisture detection (Cox and Lindner 1991; Pope et al. 1992). Recently, they have been proposed for monitoring moisture (Mitschke 1989; Muhs 1992; Tomita, Tachino, and Kasahara 1990; Udd 1991). These sensors detect environmental effects, such as the presence of moisture, in two ways. First, the optical fiber can be used strictly as a light carrier to and from a "black box" that impresses information on the light beam. The light then propagates through the fiber to a remote receiver. The black box can contain any of a number of mechanisms that will modulate or transform the light beam. When used in this manner, the fiber acts as an extrinsic sensor.

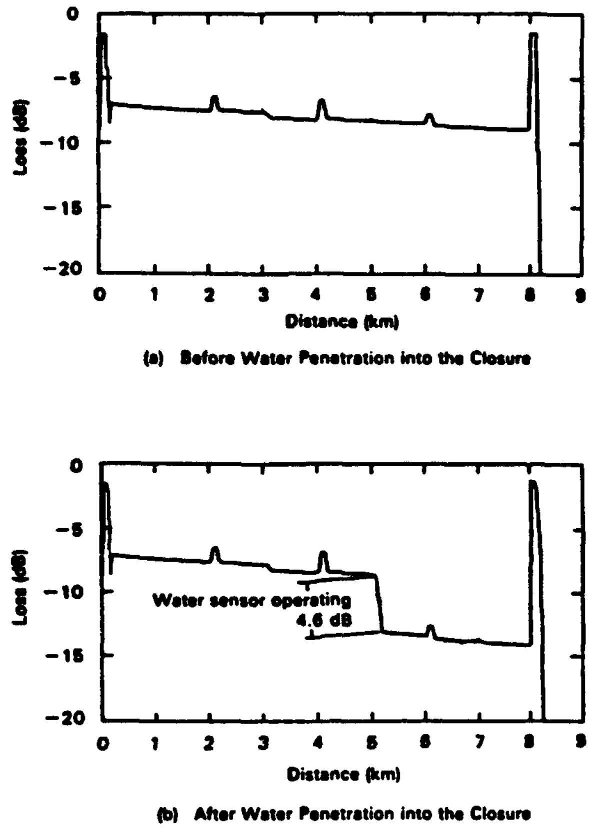
One type of extrinsic sensor has been used to monitor the presence of moisture in fiber optic cables. The sensor (Figure 5) consists of a movable bender and an absorbent material. When water surrounds the sensor, the absorbent material will expand. This expansion pushes the bender against the fiber, which deforms it. The bend causes an optical loss that can be detected using Optical Time Domain Reflectometry (Figure 6). For this type of sensor, the segment of fiber at the bender location is the sensor portion of the fiber and the remaining length of fiber functions as the transmission medium.

The second detection method using fiber optics, intrinsic sensing, relies on the properties of the optical fiber itself to convert the environmental stimulus (i.e., presence of moisture) into modulation. One particular sensor makes use of a



(Tomita, Tachino, and Kasahara 1990, ©1990 IEEE)

Figure 5. Diagram of an extrinsic fiber optics sensor with a movable bender.



(Tomita, Tachino, and Kasahara 1990, ©1990 IEEE)

Figure 6. Waveforms before and after water penetration.

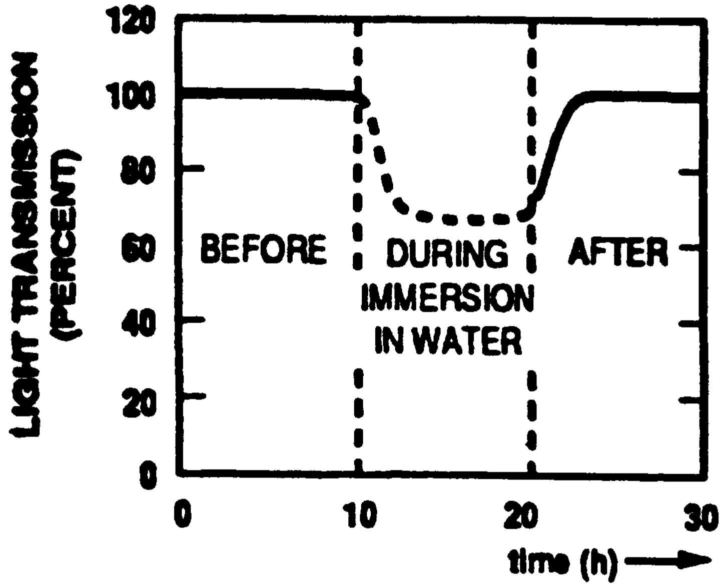
silicone rubber optical fiber, which when immersed in water, allows hydroxyl ions to permeate through its outer buffer and become embedded in the cladding (Muhs 1992). This influx of ions will attenuate light and alter the transmission characteristics of the fiber. Moisture is sensed by monitoring deviations in the transmission (Figure 7). The same segment of fiber functions as both the sensor and transmission medium in intrinsic sensors.

For both the extrinsic and intrinsic fiber optic sensors, a calibration curve is required to relate the response of the sensor to the moisture content of the material.

Signal

The signal type, usually dictated by the sensor being used, may be an electrical current or voltage, electromagnetic wave, radio wave, or light. These signals can be grouped into two categories: continuous and on/off.

A continuous signal is one that is constantly transmitted and monitored. This type of signal allows the progression of the stimulus to be determined. For a PRLDS application, continuous signals will provide a means of tracking changes in the moisture content in the roofing system over time. With most sensors using



(Muhs 1992, reprinted from the July 1992 issue of *Photonics Spectra*, ©Laurin Publishing Co., Inc.)

Figure 7. Transmission loss in a silicone rubber optical fiber due to water penetration.

this type of signal, a calibration curve must be established to relate the signal to moisture levels. Establishing the relationship is accomplished by measuring the signal level at known levels of moisture content. The resulting curve may be only accurate for the particular type of insulation it was calibrated for; a different curve must be developed for each type of insulation that is to be monitored. The signal processing unit uses the calibration curve to determine the moisture content of the insulation for a given signal level.

An on/off signal is transmitted on an event-by-event basis. Time histories are not captured with this type of signal; however, they can be used to record the incidence of singular events. A calibration curve is not required. A good example of this type of signal is the thermostat of a furnace. Once the thermostat is set, the furnace will only operate when the temperature falls below the preset level. The operating switch to the furnace is only closed while the temperature is below the preset level. For a PRLDS, the signal level for what may be defined as "wet" is established as a threshold level. When this threshold level is reached, the signal is interpreted by the signal processing unit as a roof leak. For some sensors, the very existence of any signal indicates a leak.

Transmission Medium

Depending on the particular sensors, different types of transmission media are used to carry the signals from the individual sensors to the signal processing unit. Signals involving electrical currents or waves require conductive wires. In this case, a pair of insulated wires connect each sensor to the signal processing unit. Resistive, capacitive, and some circuit-bridging sensors use electrical wires for the transmission medium. With fiber optic sensors, optical fibers serve as the transmission medium, carrying light to and from the sensing segment. Air is the transmission medium for the water-activated, battery-transmitter, circuit-bridging sensor, which emits signals via radio waves.

Table 1 shows the different transmission media which can be used with the various types of sensors.

Signal Processing Unit

The primary function of the signal processing unit is to relate the signal being received from the sensor to the stimulus being detected. For a PRLDS, the unit would contain a processor that reads the signal emanating from the sensor and deciphers the information to determine the location of the triggered sensor and, in some cases, the level of moisture in the system. If required by the particular sensor, the processor may use a calibration curve to relate the signal to the stimulus.

Once a signal from a triggered sensor is processed, information can be displayed on a monitor or printed out, an audio or video alarm can be activated, or some other action can be generated. With today's technology, the capabilities of the signal processing unit are almost limitless.

System Configuration

A diagram of a PRLDS is shown in Figure 8. In this particular configuration, individual sensors are arranged in a grid pattern over the entire field of the roof, spaced at equal intervals. At locations where there is a higher probability of leak occurrences, such as around roof penetrations and perimeter flashings, the sensors may be spaced closer together.

A rooftop relay unit, capable of accepting signals from all sensors on the roof, may be used to consolidate the individual transmission lines from the rooftop and relay the signals to the signal processing unit located within the building or offsite. The signal processing unit could be designed to activate a modem to relay the information to a central monitoring station at another site. This option would allow multiple roofs to be monitored from a single location.

Table 1. Sensor-transmission media matrix.

	Transmission Media		
Sensors	**Electrical Wires**	**Optical Fiber**	**Air**
Resistive	X		
Capacitive	X		
Fiber Optic		X	
Circuit-Bridging	X		X

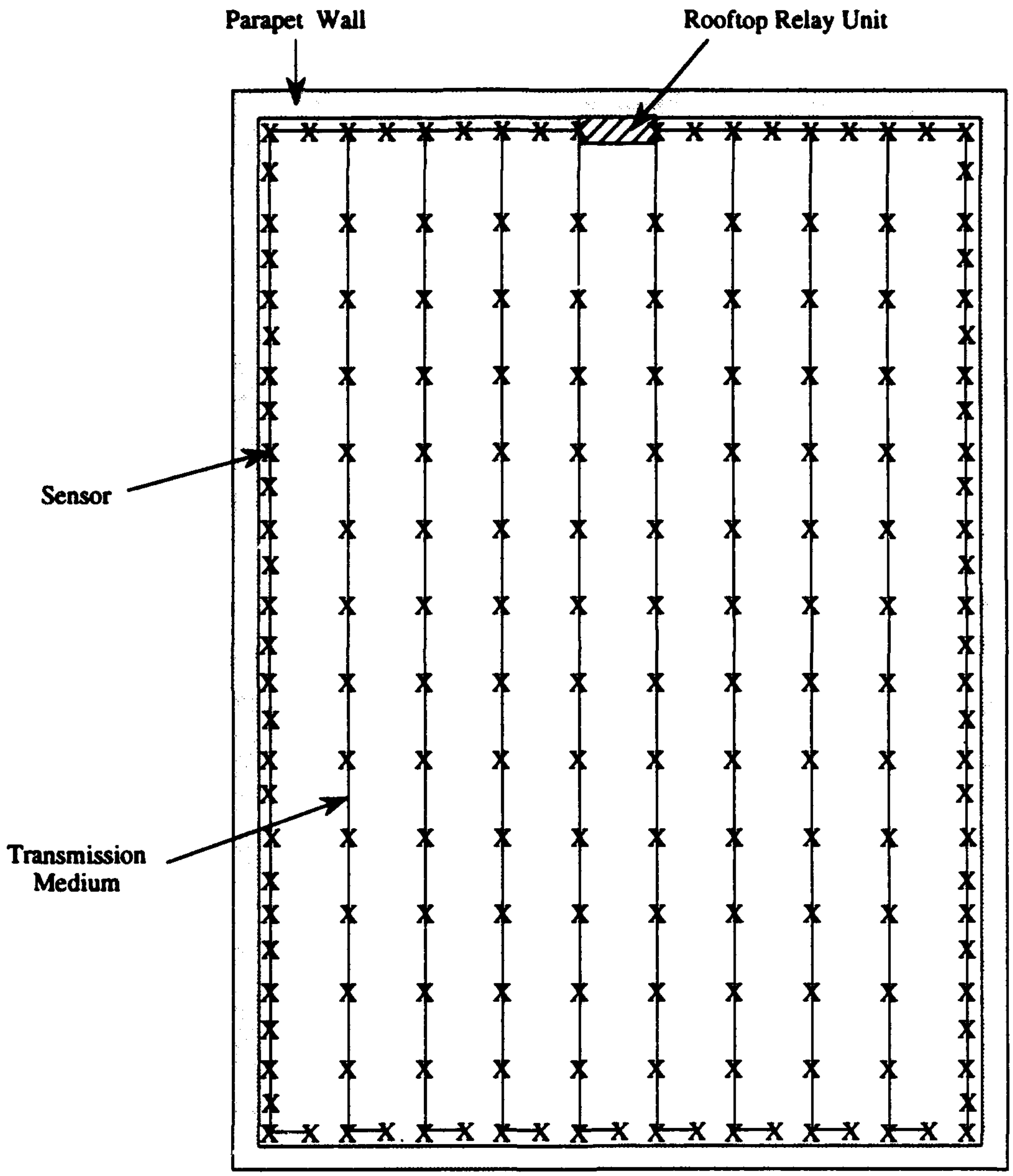


Figure 8. A PRLDS configuration.

Sensor Spacing and Resolution

Of primary importance to the effectiveness of any PRLDS is the frequency or spacing of the sensors. This spacing determines the "resolution" of the system. The resolution requirement should be based on economic considerations and the interior use of the protected structure. If the roof is protecting extremely sensitive material (i.e., liquid sodium or mainframe computers), a tight resolution with short spacing between sensors will be required. If the interior is less sensitive to damage, and the primary requirement of the PRLDS is protection of the roofing investment itself, greater spacing between sensors would be acceptable.

The proper choice of sensor spacing to achieve adequate coverage would also depend on the extent to which liquid water can migrate laterally through the roofing system. This would vary with the type of insulation (i.e., closed cell vs. open cell), method of attachment, and other design and construction details for the roofing system.

A high resolution PRLDS, using individual point sensors, would have sensors placed in a closely spaced grid pattern throughout the entire roofing area. Moisture that enters into the roofing system would need to travel only short distances laterally before being detected. This would result in the leak source being in close proximity to the detecting sensor. This system would require a dense distribution of sensors and transmission lines.

For a low resolution PRLDS requiring fewer sensors, a grid pattern with larger sensor spacing could be used or the location of the sensors could be restricted to suspected problem areas and at existing valley lines. The valley sensors would help ensure that intrusive moisture that runs down the slope of the deck will probably encounter several sensors. Information concerning the direction from which the moisture came and the general roof area encompassing the leak source could be obtained. Using this simple information, an experienced roofing repairman could find the location of the leak.

3 Performance Requirements

The sensors and transmission medium of a PRLDS are physically integrated into the roofing system. These components can be evaluated against the following performance characteristics: reliability, compatibility, durability, and maintainability.

Reliability is defined as the ability of the sensors to rapidly identify anomalies in the roof covering throughout the lifetime of the roof. The sensors should also be capable of detecting moisture intrusion efficiently without their signal accuracies fluctuating over time. They should be able to distinguish between moisture from leaks and low levels of residual moisture in the roofing system from other sources.

The compatibility characteristic defines the ability of the PRLDS to be integrated into a roofing system, both during and after installation. Interruptions caused by the placement of the system components should be carefully planned so as not to hinder the activities of the roofing crew during construction. Excessive interruptions could compromise workmanship. Furthermore, the presence of the PRLDS should not degrade the waterproof integrity of the roofing system throughout its service life.

Component durability relates to the ability of the sensors and transmission medium to withstand the harsh rooftop environment. The system components must be able to endure normal mechanical loading, thermal loading, and temperature cycling without diminishing performance.

Maintainability considers the ability to diagnose problems and failures of PRLDS components and make necessary repairs. A maintainable PRLDS should be capable of self-monitoring the components, or their failure rate must be determined to be acceptably low. If defects occur, they should be able to be located and repaired or replaced in a timely manner while keeping the roofing system watertight.

Reliability

Functionality

For any PRLDS to function properly, it must provide, in combination with the roofing assembly, a means for collecting intrusive moisture and channeling it to the sensors. An efficient way of accomplishing this is to place the sensors on an essentially watertight membrane. A vapor retarder can function very well as a moisture channeling membrane. Vapor retarders are commonly used in cold climates or over high humidity interiors to prevent excessive vapor migration from within the building into the roofing system. Another means of providing moisture channeling is to use a layer of adhered closed-cell insulation boards with taped joints. Placing the sensors and transmission medium into a roofing system that will achieve the necessary moisture channeling must be done in a way that will not damage the components.

As described previously, capacitive and resistive sensors operate on the principle that the electrical property of the insulation material will change as it absorbs moisture. Some types of roof insulation will absorb water quickly while others are relatively nonabsorbent (Tobiasson 1983). To ensure timely leak detection, PRLDSs using these types of sensors will probably function best with roofing systems having absorbent insulations such as perlite and fiberboard. If used with nonabsorbent insulations (i.e., polyisocyanurate), excessive amounts of moisture may be allowed to enter the roofing system before the insulation absorbs enough moisture for the sensors to indicate a leak.

Some circuit-bridging sensors, such as the water-activated battery, require an appreciable quantity of free moisture (i.e., 2 ounces*) to activate the sensor. These sensors are likely to function better with roofing systems with insulations that are relatively nonabsorbent and that allow free moisture to flow laterally. Examples of roofing systems of this kind are loose-laid or mechanically fastened systems having closed-cell insulation.

Signal Fluctuations

Alteration of the signal levels being transmitted by a sensor over time will result in false readings by the PRLDS system. Possible causes for the alterations include changes in sensor calibrations, temperature effects, and changes in the conductivity of the roof insulation.

Resistive, capacitive, and fiber optic sensors rely on calibration curves to relate a measured property to the amount of moisture in the material. A calibration procedure must be performed before installing the sensors in the roofing system. If the sensors lose calibration during service, it will be necessary to cut the roof membrane, replace the sensors, and restore the watertight integrity of the roof with repair patches. It is best to use a sensor that will minimize the need for recalibration or replacement. Of the three sensors types, resistive sensors appear to be the most vulnerable to decalibration.

Temperature can significantly alter the response of fiber optic sensors through the photoelastic effect (Udd 1991). This effect describes the change in the index of refraction of a material with the application of strain. Temperature changes can induce thermal strains in the optical fibers. As a result, altered signals due to large temperature changes could be mistaken for moisture. The silicone rubber optical fiber can experience a 5 percent loss over a 100 °C temperature range (Muhs 1992). Optical fibers made from other materials may experience even larger losses. This photoelastic effect can be compensated for by using a reference arm that is only subjected to temperature variations and not moisture. The response from the reference "arm" can be combined with the response from the sensing arm to obtain the response due to moisture only. The effect of temperature on electrical capacitance and resistance measurements in a PRLDS

*A metric conversion table is on page 38.

application are not expected to be as great as the effect of moisture (Schmugge, Jackson, and McKim 1980).

The conductivity of a material, such as roofing insulation, not only depends on its internal conductivity, but also is a function of the ion concentration in the material. Studies using resistive moisture sensors in soils indicate that the calibration curve is highly dependent on ion concentration. Unless the ion concentration can be controlled, resistive sensors may require frequent recalibration (Schmugge, Jackson, and Mckim 1980). The ion concentration of roof insulation will depend on the ion concentration of the moisture it has absorbed. If the rain water has a high ion concentration or if it picks up ions from substances deposited on the roof, salts for example, these ions will become deposited in the insulation and alter resistance measurements.

Sensitivity

The reliability of a particular sensor also depends on its sensitivity to water vapor. To function as a part of a PRLDS, a sensor must be capable of distinguishing between free moisture from roof leaks and seasonal cycling of water vapor in and out of the roofing system from the building interior. Studies performed at the Cold Regions Research Engineering Lab (Tobiasson and Ricard 1979) indicate that most types of roof insulation remain dry even when large amounts of water vapor are passing through them, unless the dew point occurs within the insulating layers. As a result, the capacitance and resistance measurements of insulation may not be largely affected by water vapor from seasonal movement. However, some fiber optic sensors, such as the silicone rubber fiber optics sensor, exhibit characteristics that make them more sensitive to water vapor. Water vapor molecules can penetrate the outer sheathing of the fiber and become deposited on the cladding. These molecules can change the index of refraction of the cladding, which can cause the transmission characteristics of the fiber to be altered and give a false response.

Compatibility

A major obstacle associated with installing a PRLDS is in integrating the process into the actual construction of the roofing system. Placing a dense mesh of sensors and transmission lines in the roof may be cumbersome and time consuming, which could lead to construction delays and may reduce the quality of the workmanship. Therefore, it is advantageous to use a PRLDS requiring a simple installation process that can be performed concurrently with the roof installation or after the roof is complete.

PRLDSs with transmission lines of electrical wires or optical fibers would be placed on the membrane surface or within the roofing assembly. Placing the wires on top provides for easier installation and accessibility to wires that become damaged after installation. The sensors also may be installed on the membrane. This process minimizes the potential for delays in the roof construction, but requires patching to maintain watertightness over the areas where the wires penetrate the membrane. Extensive patching would likely be required over the transmission lines to secure them and provide protection from damage. For the purposes of obtaining quality and retaining the roofing contractor's responsibility for the roof installation, patches will probably need to be performed by the roofing crew.

If the transmission lines are to be placed under the membrane, the placement of the sensors and lines must occur during the construction of the roofing system. This process of laying an intricate network of sensors and wires will require extensive planning and painstaking care to avoid construction delays.

Regardless of whether optical fiber or electrical wires are used, extra precaution will be required to avoid damage to the lines by driven fasteners.

Durability

To be practical for use in a roofing application, the sensors and transmission medium must be able to withstand mechanical loading from roof traffic. Of the four types of sensors considered, the fiber optic sensors exhibit the most vulnerability to mechanical loading. Typically, optical fibers are extremely brittle and require great care during handling to avoid damage (Udd 1991). Large mechanical loads or differential movement in the roofing system could damage the fibers causing them to give false readings. When an optical fiber is bent beyond its bend radius, the core begins to deform and transmission losses occur (Muhs 1992). This loss may be mistaken for a loss due to the presence of moisture. The only method by which to protect the fibers from such loads would be to place them inside a conduit that would allow moisture to pass through but prevent the fibers from being subjected to mechanical loading and deformation.

Electrical transmission lines will be much less susceptible to damage unless they are located on top of the membrane. If they are on top, they must be protected by patches so normal roof traffic does not damage them. Their durability would depend on how well the patches bond to the membrane.

The resistive, capacitive, and circuit-bridging sensors typically are self-contained units that would seem to be relatively unaffected by differential movement within the roofing system. However, they may be susceptible to damage from impact loading caused by normal roof traffic and other rooftop abuse. Sensors placed below the insulation would have more protection from this type of damage than sensors placed just under the membrane.

Maintainability

It is desirable for a PRLDS to be able to monitor the components to ensure that the system is able to function. Most systems using continuous signal sensors will have the capability of monitoring damage to the sensors. The returning signal from a bad sensor will be distinguishable from levels indicating the presence of moisture or dry insulation. For example, a break in a fiber optic cable will result in a dramatic loss in its transmitting capability. Using a method known as Optical Time Domain Reflectometry (OTDR), the location of the break along a long length of fiber can be easily determined (Udd 1991, Muhs 1992). For resistive sensors, a faulty sensor may result in an open circuit, which can be detected readily. Circuit-bridging sensors that operate in a continuous mode will be able to determine the occurrence of faulty sensors through such means as detecting deviations of the signal in the opposite direction of those caused by moisture.

The method used to detect damage to electrical wires will depend on the mode of operation of the attached sensor. A damaged line will result in an open circuit and can be detected easily by the signal processing unit. However, locating the damaged section of wire can be done using TDR. In some cases, this may be a difficult and costly process. If the lines are on the top of the membrane, this would involve removing the patches over the lines. If the lines are buried in the roofing layers, locating the damage will require removing part of the roofing system.

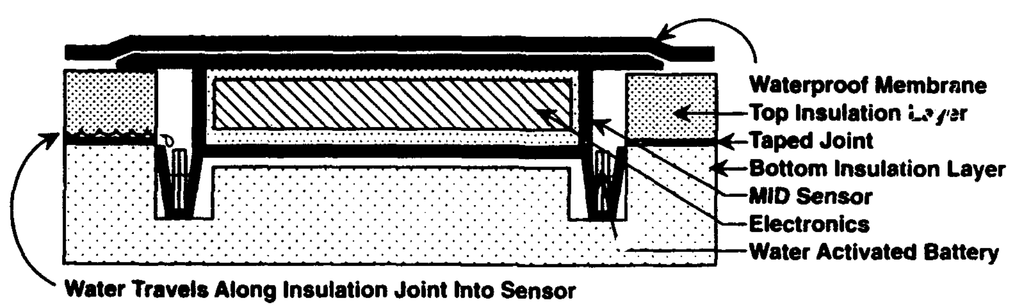
4 Review of PRLDSs and Moisture Sensor Technologies

A literature survey was conducted to identify PRLDSs and specific sensor technologies that could be incorporated into a PRLDS. The existing PRLDSs vary in their stages of development from being a conceptual design to a fully designed and marketed system. The sensor technologies presented are representative of those exhibiting potential for a PRLDS application. Some of these have not been used for roof leak detection but have been used for moisture detection in various other applications.

Water-activated Battery/Transmitter

A water-activated battery/transmitter is the sensor in a PRLDS system being marketed and sold. The system (Bryan 1986; MID 1992), which was patented in 1986, consists of an array of sensors that emit pulse coded signals via radio waves to a remote receiver functioning as the signal processing unit. A cross-sectional view of an installed sensor is shown in Figure 9. The sensor is 5-1/2 in. in diameter and 1 in. high and powered by a water-activated battery based on 1950's sonobuoy technology. The electrolytes of this water battery are dry until contact with water is made. When 2 oz of water accumulates in the surrounding trough, a strong reaction is initiated. This reaction produces the current needed to activate the radio. Once activated, the transmitter can operate continuously for 1 to 3 hours.

The signal is picked up by the receiver, which can be located as much as 300 ft away from the sensor (or even greater distances if the receiver has a rooftop antenna). The receiver records which sensor was activated and the time of



(Courtesy of MID Systems, Inc., 1992)

Figure 9. Cross-sectional view of water-activated battery/transmitter.

activation. With the aid of a map recording the location of each of the sensors, the leak can be located quickly. If more than one sensor is activated, the receiver keeps track of the sequence in which the signals were received.

Each transmitter broadcasts on ten different frequencies. The receiver unit scans all ten frequencies so that in the event that one frequency is jammed by outside interference, the signal will still be picked up. This feature allows signals to be received in areas of high radio broadcast activity.

A receiver can monitor up to 5000 individual sensors, but can only hold a maximum of 250 actuation events (occurrences of triggered sensors) in memory. The unit is equipped with a nonvolatile memory that can be scrolled back to review all actuation signals occurring since the last system reset. In some situations, this capability could allow the path of the moisture to be traced by tracking the sequence of activation events. During a power failure, a battery can keep the receiver running for up to 72 hours. The receiver can be monitored manually or can be programmed to activate a dial-up modem. The former would be used when only a single building needs to be monitored, the latter for monitoring several buildings.

The sensors are installed after the insulation has been placed and before the membrane is installed. The roofing system must have at least two layers of insulation, with the sensors being placed on the bottom boards at predetermined intervals along the joints of the upper layer. The joints of the bottom insulation boards are taped or a layer of polyethylene is installed on top of them. Figures 10, 11, and 12 show a typical installation sequence. After the top layer of insulation is in place, a hole is cut in the top board and the sensor is inserted with its top surface flush with the top of the underlying insulation board. The sensor is placed at the corner of two insulation joints. This placement allows water to pool on top of the bottom layer of taped insulation, and follow the joints of the top insulation boards to the sensor. With the battery portion of the sensor recessed below the top of the taped layer, the water is directed to the battery and activates the radio. This system configuration is intended primarily for closed-cell or high density roof insulation.

The electronics of the sensor are housed in a plastic case, which provides protection from careless handling at the work site and from static loads of as much as 350 lb. The sensor has also been designed to withstand temperature extremes of -40 to +90 °C.

The ability of the sensor to function properly after long term exposure to high humidity may be adversely affected. Relative humidity above eighty percent will cause the battery to degrade over time. A method of checking the operational integrity of a sensor has recently been developed and is currently being tested. Unlike electrically-based sensors, each sensor unit will need to be checked independently on the rooftop by a technician.

A very positive attribute of the system is that it transmits a radio signal, eliminating the need for hardwiring and alleviating any concerns with the performance of the transmission medium.

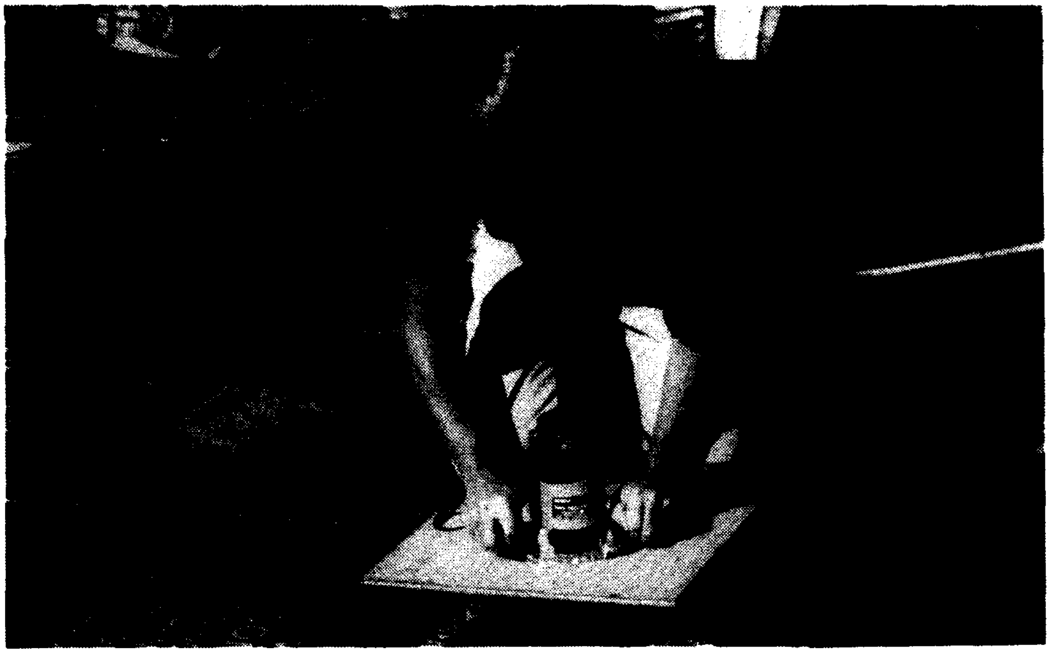


Figure 10. Hole being cut in insulation for sensor.

Resistance Probe

This system is based on resistance measurements and consists of an array of probes distributed across the roof area in a grid pattern, as shown in Figure 13. The signal processing unit sends out a series of low frequency, constant current pulses that are transmitted to the probes through a network of wires (Industrial Options 1992). A cross section of an installed probe is shown in Figure 14. The probe consists of two prongs in parallel with a nominal resistor. The effective resistance of the probe can be expressed as:

$$V_{eff} = \left(\frac{1}{R_{nom}} + \frac{1}{R_{ins}} \right) - 1 \quad \text{[Eq 2]}$$

where R_{nom} is the value of the nominal resistor and R_{ins} is the resistance of the insulation between the prongs. The effective resistance of the probe will decrease as the insulation becomes wet. This will cause a drop in the voltage being monitored by the signal processing unit. The decrease in the voltage from the nominal, dry level triggers an alarm that indicates the presence of moisture. A voltage

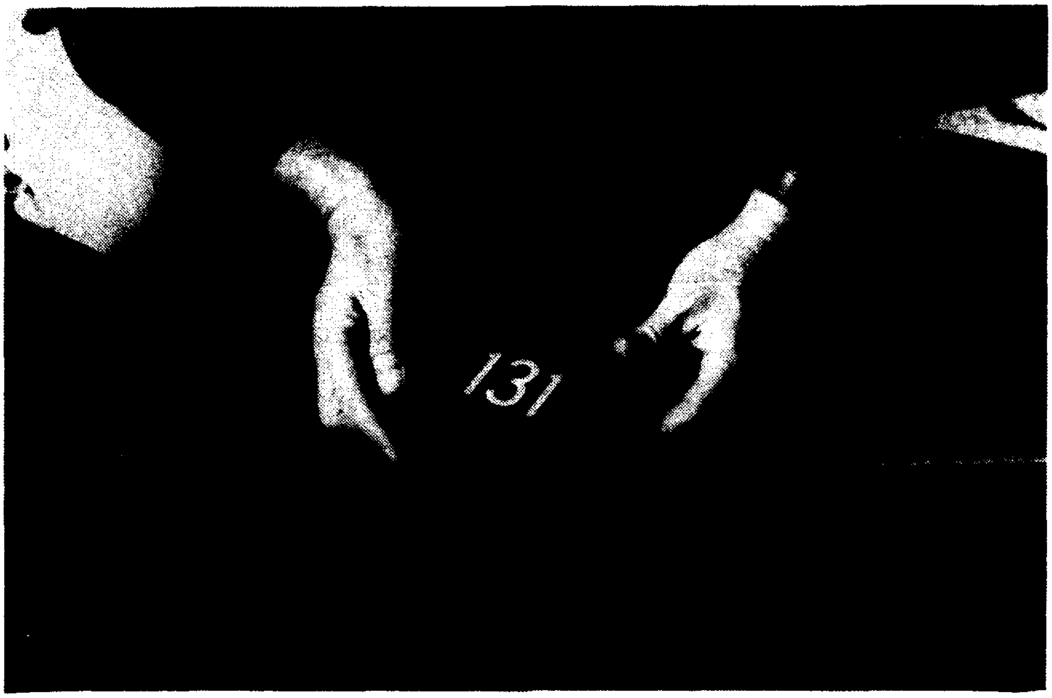


Figure 11. Sensor being inserted in insulation.

Figure 12. Installation of built-up roof membrane over sensor.

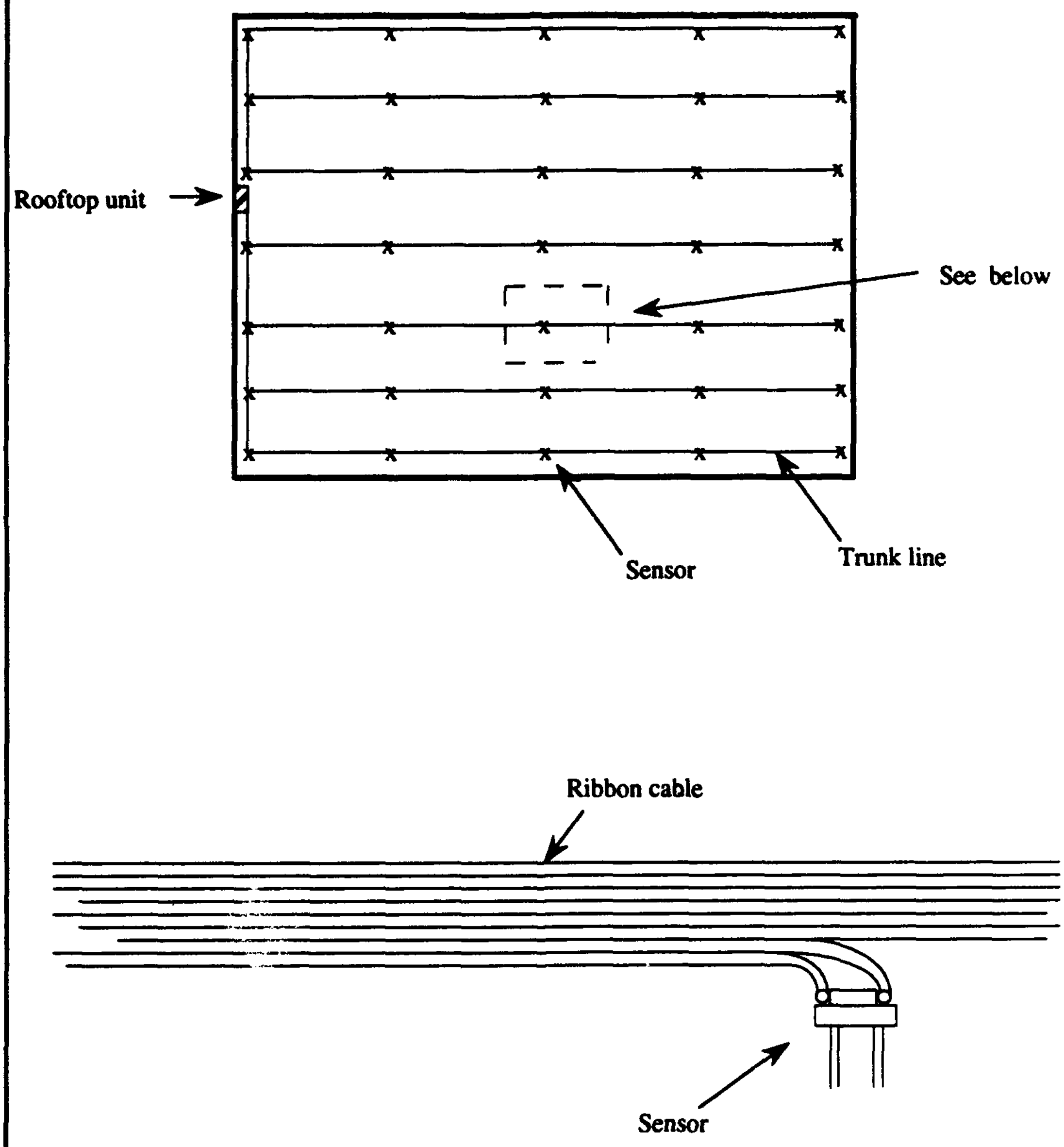


Figure 13. System configuration for resistance probe sensor.

signal higher than the nominal level indicates damage in circuit (Figure 15). The damage may be a broken wire or a faulty sensor. If no excessive moisture is present, the corresponding voltage signal is undisturbed. Figure 15 shows a representation of the three signal levels.

The sensor configuration used by this system also allows it to sense added moisture in an already wet section of insulation. The electrical current passed through the probes can be adjusted so the nominal, dry voltage level can be achieved in the presence of moisture. As a result, the sensor can be used in a situation where wet insulation exists, but it is desirable to monitor further moisture gain. This characteristic differs from those circuit-bridging sensors that are single event sensors and must be replaced once activated.

The electrical wires that function as the transmission medium are grouped together along trunk lines using ribbon cables (see Figure 13). These trunk lines run parallel to each other and are brought to a central collection point (rooftop relay unit), which would likely be placed at the roof perimeter. The group of wires can either be connected to a signal processing unit within the building or to a dial-up modem for remote monitoring.

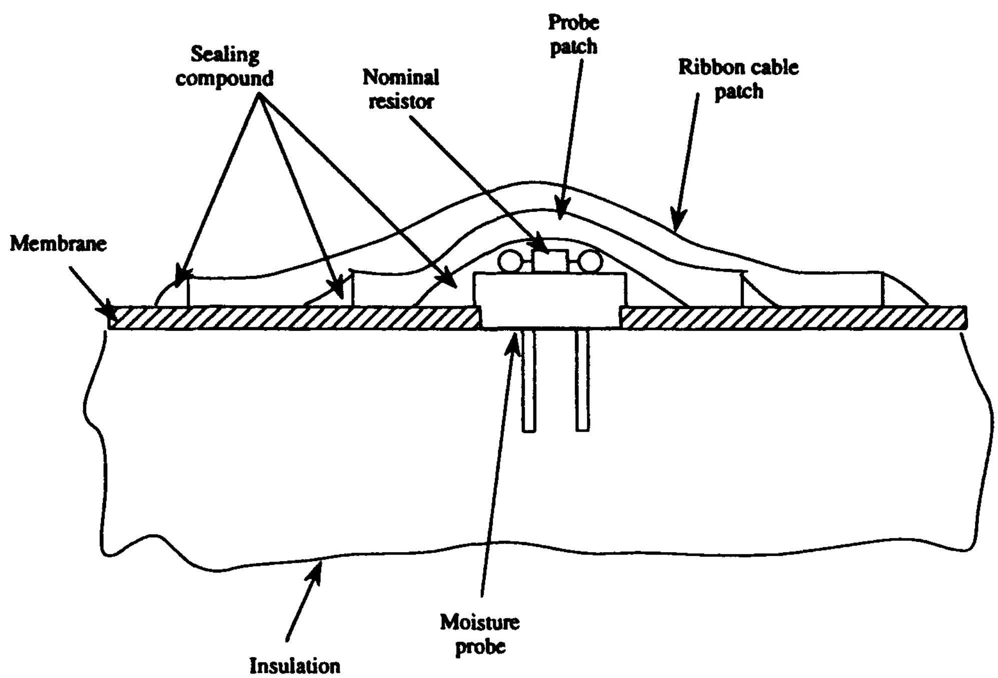


Figure 14. Cross-sectional view of an installed resistance probe.

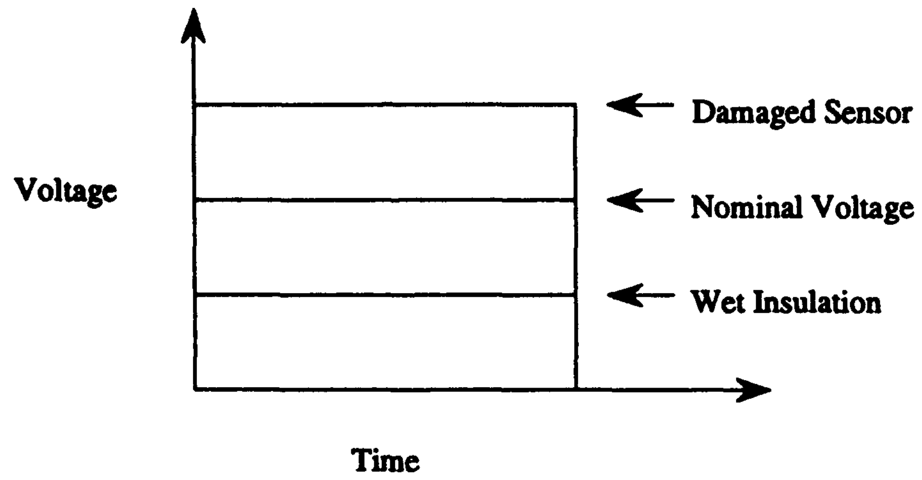


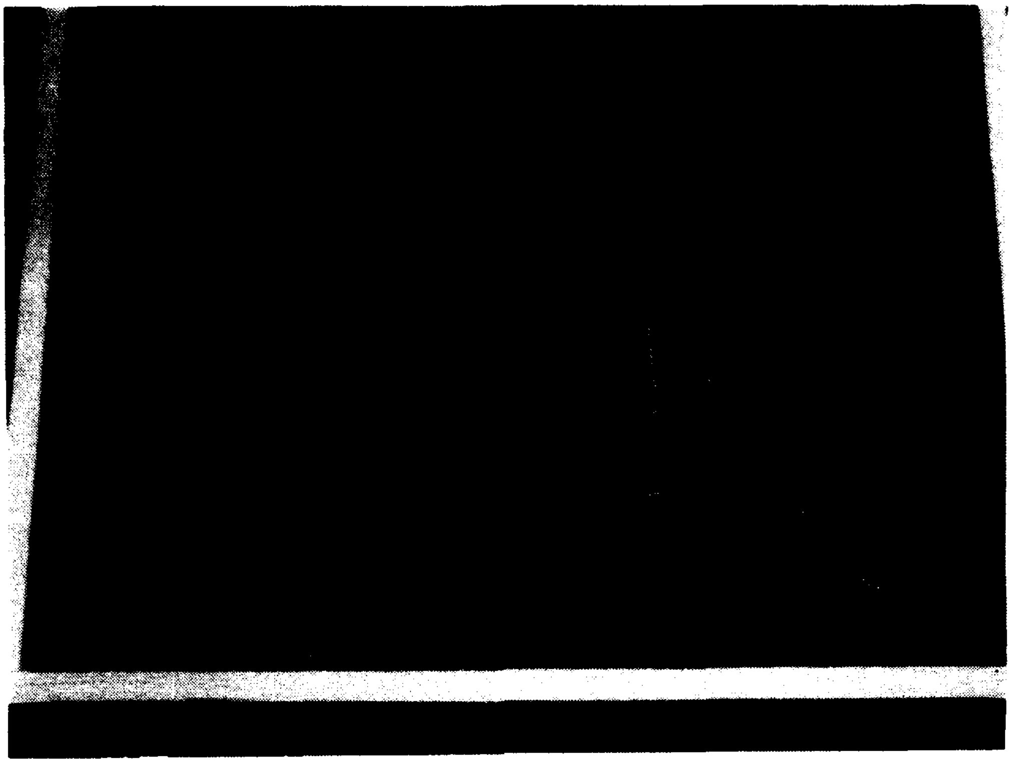
Figure 15. Signal levels for resistance probe.

As recommended by the system designer, the sensor is installed after the roof membrane is installed and involves four steps (Figure 16). At each sensor location, a small incision is made in the membrane to allow for insertion of a probe. The probes are 1/2 in. wide and 1/2 in. tall. Once the probes are in place, sealant is applied around the incision and a circular patch placed over the top. The trunk lines are also covered by patches, which serve as a third seal around the incision and as a means of protecting the cables. Roof membrane material and the manufacturers' recommended seaming procedures must be used to make the protective patches over the sensors and wires.

Pin Probe

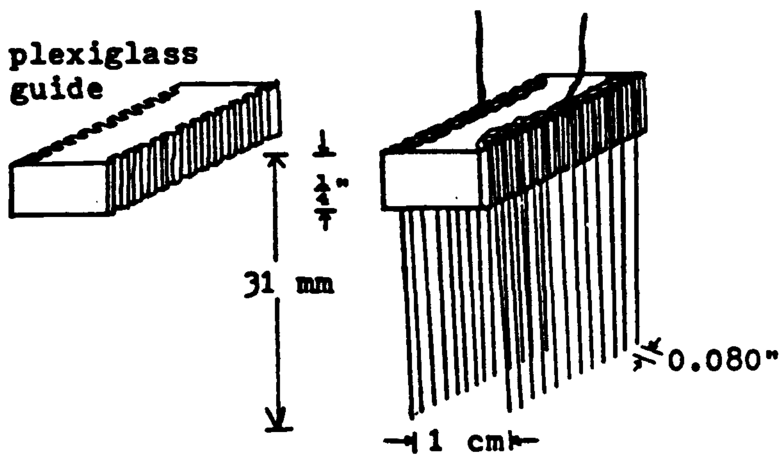
The "pin probe," a capacitive sensor, was developed by researchers from the Massachusetts Institute of Technology (MIT) in 1987 for measuring moisture content of open pore thermal insulation (Motakef and Glicksman 1989). The sensor consists of two parallel plates composed of twelve closely spaced stainless steel pins, with a rigid plexiglass spacer separating them (Figure 17). The probe is 31 mm long and 10 mm wide and has two leads, one connected to each plate, to transmit the signals. The sensors are placed at the joints of the insulation boards with the pins inserted into the insulation.

The sensor is driven by an alternating current source through shielded and grounded transmission wires at a frequency determined by the capacitance range of the insulation being used. Generally, the lower the capacitance range of insulation, the higher the required frequency. The probe output is converted to a direct current signal that can be continuously monitored by the signal processing unit. The electrical capacitance between the two rows of pins increases with moisture content in the insulation.



(Courtesy of Industrial Options 1992).

Figure 16. Steps in the installation process for resistance probe system.



(Motakef and Glicksman 1989. Couresty of Oak Ridge National Laboratory.)

Figure 17. Diagram of pin probe.

The pin probe has proven to be a sensitive humidity indicator for laboratory use. In its current form it has a variance of moisture determination of 10 percent and a "tipover point" when liquid bridges the electrodes. This sensor has exhibited appreciable sensitivity to temperature; resulting in diurnal variations in tests (Motakef and Glicksman 1989). This problem might be solved by installing the sensors between layers of insulation or by using custom software to eliminate the diurnal effects of temperature. The sensors require calibration for the particular type of insulation in use.

A data acquisition capability has been developed for taking measurements automatically by a computer. The computer reads the input and output voltages and calculates the capacitance from them. The multipin probe has not been subjected to additional developmental work since a 1989 study (Pedersen et al. 1992). Currently, calibration data exists for fiberglass and phenolic insulations.

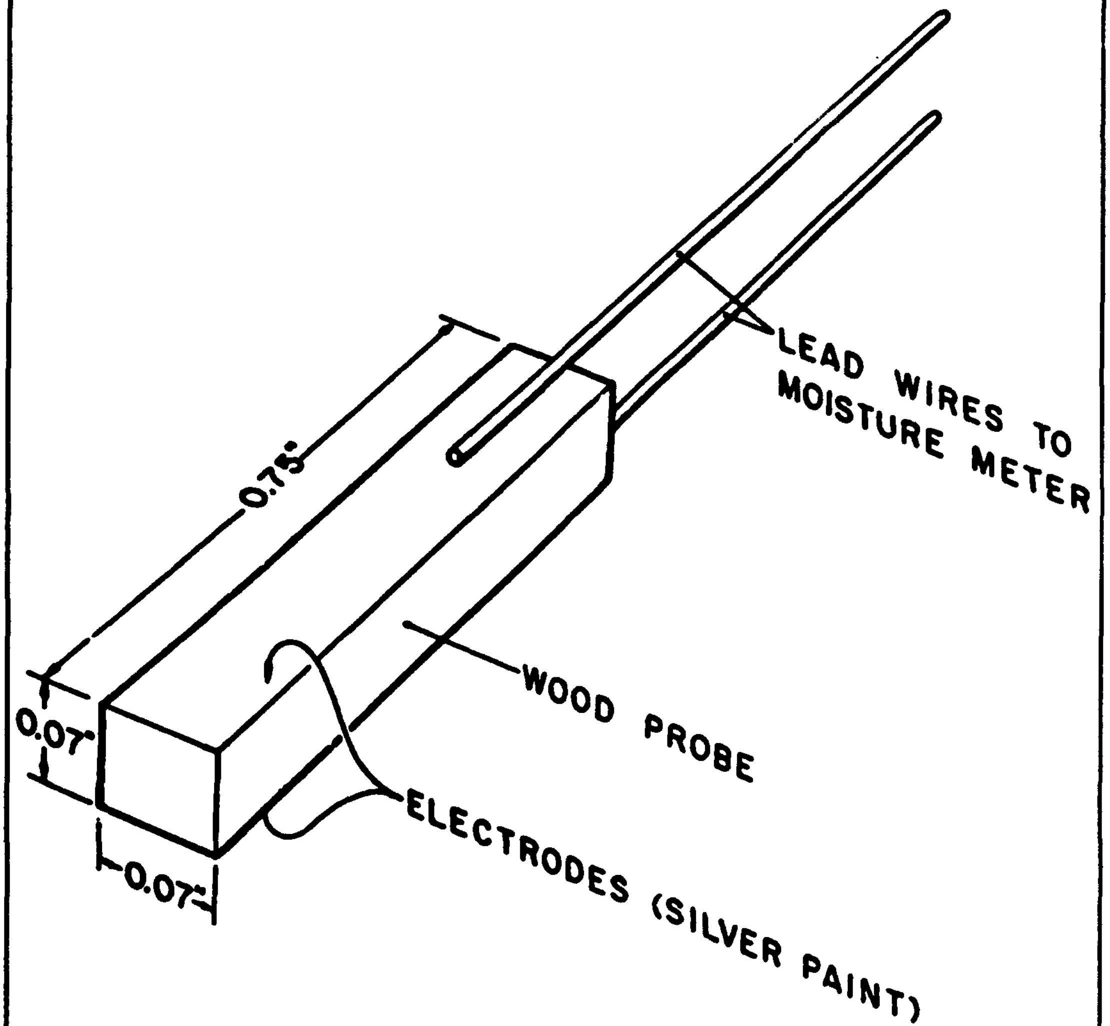
Long term durability of the pin probe is unknown at this time. Rusting of the stainless steel pins has been experienced during testing. The pins currently being used are simple stainless steel dressmakers pins and are not made of an architectural stainless steel. The other components of the probe, including plexiglass, copper wire, and solder, have not had problems.

Wooden Probe

The U.S. Department of Agriculture Forest Products Laboratory (FPL) in Madison, WI, has been using a wooden probe design since 1966 to sense moisture in wood (Duff 1966). The wooden probe sensor in its current form is a piece of soft wood 3/4 in. long and .07 in. square (Figure 18). The top and bottom surfaces of the probe are painted with conductive silver paint. Electrodes are then glued to the silver paint. The electrodes and paint allow the probe to function as a capacitor. The wood is naturally hygroscopic; as the wood absorbs moisture from its surrounding, the capacitance value of the probe changes. The probe measures accurately to within 1 percent of moisture content. Minimum and maximum temperatures at which the probe can maintain this level of accuracy are 32 °F and 130 °F, respectively.

The probe can be inserted between layers of insulation or placed on top of a watertight vapor retarder. The small size of the probe allows easy insertion into a soft material like polyisocyanurate insulation. In dense materials such as concrete decking or wood blocking, the probe can be inserted into a small drill hole. The sensor requires that the transmission of the signal be through wires covered with insulation of high electrical resistance.

The wooden probe suffers from electrochemical deposition problems over time. When continually exposed to high levels of moisture, the transport of silver ions into the wood during polarization has degraded the probe's measurement accuracy. One long-term test extending over 3 years in an exterior wall with high relative humidity rendered some of the probes useless. New techniques for charging the capacitor may be devised to delay this onset of ion transfer.



(Duff 1966).

Figure 18. Diagram of wooden probe.

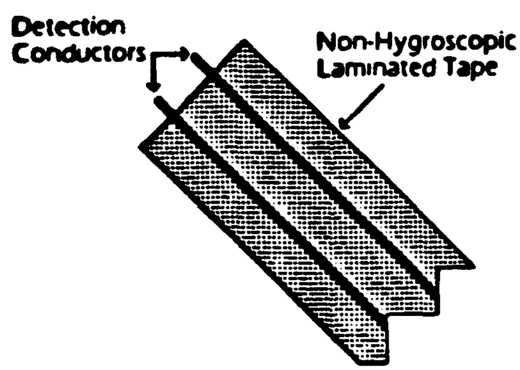
Moisture Detection Tape

The moisture detection tape is a circuit-bridging sensor. The sensor and a signaling system have undergone more than 10 years of development (Ross and Sontag 1987) (Figure 19). This sensor, which is designed to last 25 to 35 years, has been used in the telecommunication industry for more than 10 years as a moisture detection system for long distance underground cable protection.

The tape has two wire electrodes with a nonhygroscopic covering that is unaffected by high humidity levels but allows water to pass between its fibers. A nominal current passing through the electrodes is continually monitored. The tipover point for the tape is liquid water. When the nonhygroscopic covering gets wet, it completes a circuit between the two wires. The presence of moisture decreases the resistance between the two electrodes, thereby increasing the current flowing in the circuit. A remote sensing unit transmits a digitally encoded signal when a deviation from the nominal level occurs; the signal is detected by customized hardware and software.

One existing application of the moisture detection tape uses a grid system configuration. The signaling equipment, which is digital and remotely programmable, can detect a leak and relay the information over telephone lines. This type of system could be used in ballasted single-ply roofing systems by inserting the tape between layers of insulation. Its use on roofing systems that use asphalt would be very limited; the accuracy of the tape is destroyed when it comes in contact with hot asphalt.

The tape serves as both the sensor and transmission medium and therefore must satisfy the performance characteristics of both components. It is not known at this time what self-diagnostic routines are built into the system. The tape is not reusable once it has become wet, and would have to be replaced after being activated.



(Ross and Sontag 1987. Reprinted from *Telephony*, April 6, 1987. Copyright 1994 by Intertec Publishing, Chicago, IL. All rights reserved.)

Figure 19. Diagram of moisture detection tape sensor.

Plywood Disc Sensor

Due to its variable resistance to electrical current, plywood can be used as a moisture probe. Oak Ridge National Laboratory (ORNL) has used a 2-in. disc of 1/2-in. plywood with two electrodes nailed into it (Courville et al. 1988). Electrical resistance between the two electrodes is calibrated to give the moisture content of the plywood disc sensor. Because plywood responds slowly to moisture, the sensor needs to be "read" only once or twice a day to function as a moisture sensor. This slow response time also eliminates the problem of diurnal changes caused by temperature.

The operating moisture range of the plywood disc sensor is 6 to 30 percent moisture by weight. The resistance of the plywood is too high to get a reading when moisture content is below 6 percent. When the moisture content is above the 30 percent tipover point, no change in the reading registers as moisture increases. Until the tipover point is reached, the plywood disc will perform as a humidity sensor. Because the sensor does not function reliably in subfreezing temperatures, proper placement of the sensor in a roofing system must be determined by calculations.

The plywood disc sensor appears to have application in all types of membrane roofing. The disc can be inserted into insulation or placed on top of a watertight vapor retarder. The data provided by the plywood disc has proven to be reliable in short-term laboratory tests. The disc must be maintained within certain temperature and humidity levels to remain useful. These levels are within the range encountered within a functioning roofing system.

Few sensors are as simple as a 2-in. circle of plywood. If treated plywood is usable, this sensor may be very inexpensive and durable.

Twisted Pair of Wires

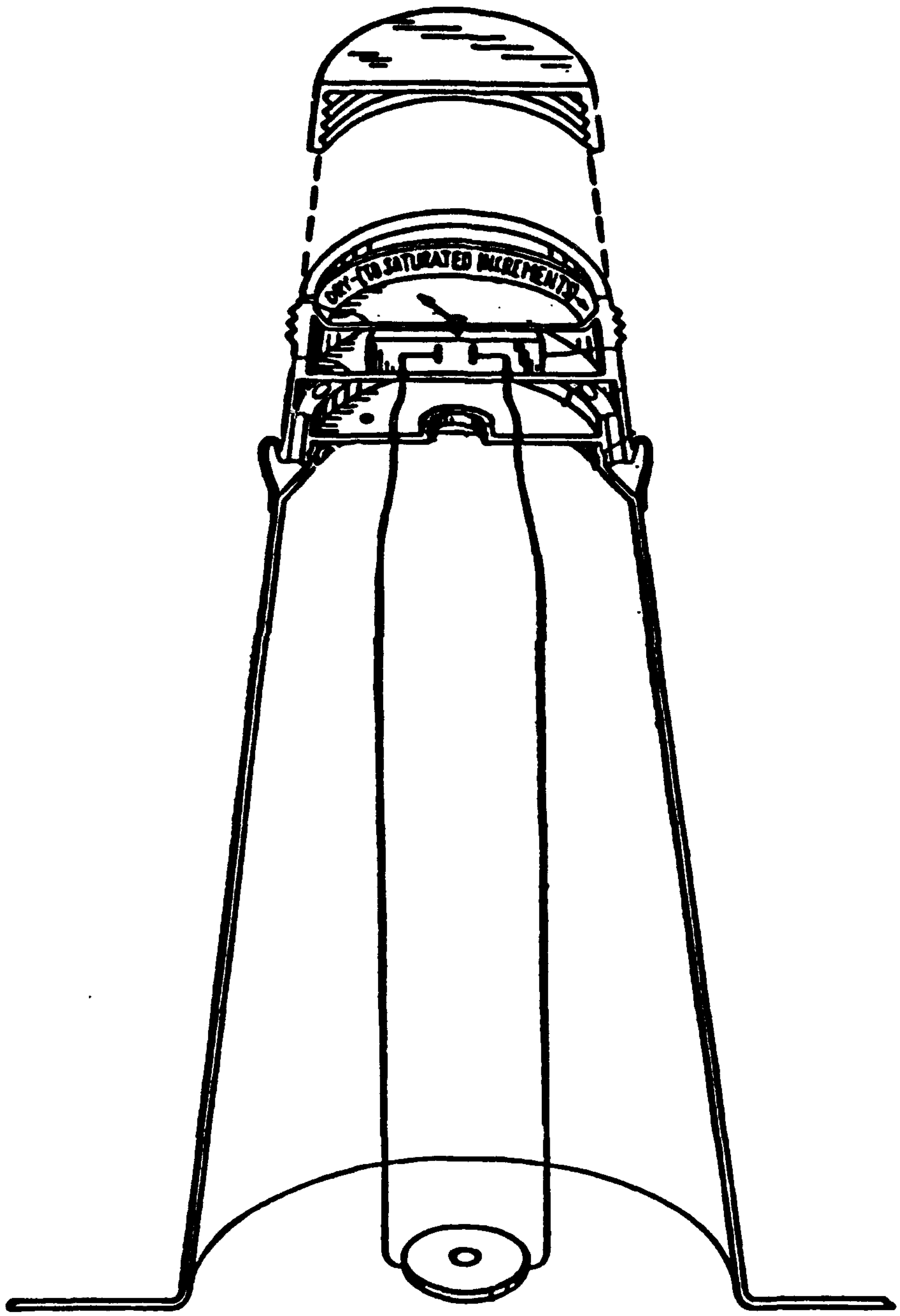
The "twisty" was invented at the Jet Propulsion Laboratory and is patented (JPL 1989). The sensor consists of two wires coated with a Teflon/sulfuric acid coating. The presence of moisture changes the dielectric behavior of the coating, which is monitored by measuring the capacitance between the coated wires. The changing capacitance varies the resonant frequency of an oscillator, which can be related to the moisture content through the use of a calibration curve. Electrical wiring serves as the transmission lines, which are connected to the bare wire tips. The sensor is extremely small (4 mm long), which would facilitate insertion into the roofing system.

The sensor has been used to measure the relative humidity of ambient air, and can also be used to test for the presence of moisture. It has not been tested for use in a roofing application. Currently, information is not available regarding the sensitivity and reliability of the twisty probe.

Breather Vent Sensor

The proposed breather vent sensor system (Nill 1992) is electrically-based and makes use of moisture sensors housed in roof breather vents (Figure 20). The system configuration can be an array of breather vents to be placed on the roof membrane or may be placed singularly where there are extra concerns for watertight integrity. The breather vent uses a removable top for quick inspection of the roof substrate and easy access for performing sensor repairs. The vent also serves as a shield for the sensor to protect it against damage from roof traffic and abuse as well as adverse weather conditions. A variety of different types of sensors can be used in this type of application. A simple system could have a dial indicator that would require manual inspection. A more advanced system would use hard-wired sensors connected to a signal processing unit.

With the moisture sensor located in the breather vent, the system's ability to distinguish between the moisture drive from the interior of the building outward and moisture from a roof leak requiring responsive maintenance, is not known. In light of drying studies (Tobiasson 1983) the ability of the sensors within breather vents to serve as real-time detectors for roof leaks needs to be demonstrated. Despite the fact that the current National Roofing Contractors Association (NRCA) Roofing and Waterproofing Manual (NRCA 1989) recommends that 1 one-way breather vent be installed for every 1000 sf of roof area, installation of roof vents is not practiced on the majority of roofing jobs in the United States. Breather vents provide extra penetration points for possible moisture intrusion and are vulnerable to damage. The quantity of breather vents needed for a PRLDS must be a consideration.



(NIII 1991.)

Figure 20. Roof breather vent with moisture sensor inside.

5 Summary and Recommendations

A PRLDS uses sensors placed in the roof that can detect water intrusion from flaws in the roofing system. An effective system can provide early detection of water intrusion and improve the ability of maintenance personnel to locate flaws in the roofs. This capability can greatly reduce damage to the roofing system, building interior, and contents.

The four major components of a PRLDS are sensors, a signal, transmission medium, and a signal processing unit. The sensors, grouped into four types (resistive, capacitive, circuit-bridging, and fiber optic), respond to leak water and transmit a resulting impulse or signal. The signal is passed through a transmission medium to a signal processing unit where it can be deciphered and processed.

Of primary importance to the effectiveness of any PRLDS is its configuration, particularly the placement and spacing of the sensors. Placement and spacing should be based on the interior use of the protected structure and economic considerations. Spacing determines the "resolution" of the system. The resolution requirement should be based on economic considerations and the interior use of the protected structure.

The sensors and transmission medium are the hardware components of a PRLDS and are physically integrated into the roofing system. These components can be evaluated against the following performance characteristics: reliability, compatibility, durability, and maintainability. The actual design of the roofing system will have a major effect on the ability of a particular PRLDS component to detect water intrusion.

This study has shown that several moisture-sensing technologies are feasible. However, there is little documented field experience with their performance.

Investigations of the more promising technologies are recommended in order to develop design specifications for membrane roofing. Laboratory testing and evaluation of these technologies should be performed with regard to the performance characteristics defined in this report. Design parameters need to be developed to achieve the best possible integration of PRLDSs with the various common roof assemblies. These parameters should include system configuration, selection and placement of components, and durability/maintainability of the PRLDSs.

METRIC CONVERSION TABLE

1 ft	= 0.305 m
1 in.	= 25.4 mm
1 lb	= 0.453 kg
1 oz	= 28.35 g
°F	= (°C + 17.78) x 1.8
°C	= 0.55 (°F-32)

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